A new approach to a model of the mammalian retina with Optically Programmable Logic Cells

A.P. González-Marcos, J.A. Martín-Pereda
E.T.S. Ingenieros de Telecomunicación. Universidad Politécnica de Madrid, Madrid, Spain

Abstract- **This paper reports a model of the mammalian retina as well as an interpretation of some functions of the visual cortex. Its main objective is to simulate some of the behaviors observed at the different retina cells depending on the characteristics of the light impinging onto the photoreceptors. This simulation is carried out with a simple structure employed previously as basic building block of some optical computer architectures. Its possibility to perform any type of Boolean function allows a wide range of behaviors.**

Keywords **– Mammalian retina, visual cortex**

I. INTRODUCTION

The retina is quite different from any of other mammalian sense organs in that a good deal of the neural processing of the afferent information has already occurred before it reaches the fibres of the optic nerve. The fibers of the optic nerve are in fact two synapses removed from the retinal receptors, and particularly as far as the rods and cones in the periphery are concerned, there is considerable convergence of information from large groups of receptors. What happens is that receptors synapse with bipolar cells, and these in turn synapse with the million or so ganglion cells whose axons form the optic nerve. These two types of neurones form consecutive layers on top of the receptor layer and are mingled with two other types of interneuron that make predominantly sideways connections. These are the horizontal cells at the bipolar/receptor level, and the amacrine cells at the ganglion cell/bipolar level.

These facts make the retina a very good place to determine some basic behaviour of neuron architectures. The interrelation among different levels and different types of responses provides a convenient working field to prove the characteristics of the elemental units adopted as building blocks for the structure. A new approach to the simulation of these configurations will be reported in this paper. The initial point is the use of elemental cells employed previously a basic unit for optical computing architectures. The difference with respect to previous approaches is that the cells to be employed here are able to perform any type of Boolean function needed. This fact makes the implemented configurations more versatile.

In the first part of the paper we will present some basic facts concerning the mammalian retina. Some ideas about the employed logic unit will be the basis for the final adopted structure for the retina. Considerations about how to employ the same type of elemental cells in the visual cortex will conclude the paper.

II. BASIC BEHAVIOUR OF THE RETINA

The retina is the first place from where the external sensations go into the living beings and hence, the first place for an initial processing of the signal. Some facts have to be pointed out. They are concerned with the way the neurons at the retina work (Fig. 1). First, three of them, namely photoreceptor, horizontal and bipolar cells, respond to light by means of hyperpolarization. These neurones do not produce action potentials. The second group, amacrine and ganglion cells, show a large variety of responses. They are action potentials in every one of the cases as well as depolarizing. Different types are reported in the literature [1]-[2]. The amacrine cells show transient depolarizing responses, including what are apparently all-or-nothing action potentials, at the onset or cessation of light. Ganglion cells could be divided into three types according to their response to illumination. 'On' units respond to the onset of illumination, 'off' units respond to the cessation of illumination, and 'on-off' units respond to both onset and cessation. Another classification is made on the basis of the action potentials produced in response to stimuli. Most cells

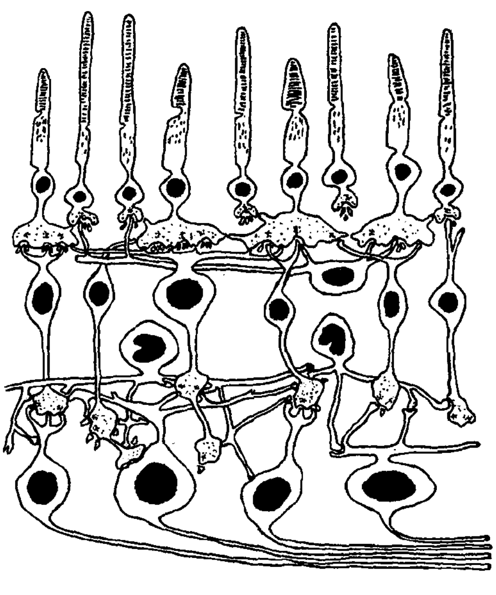

Fig. 1. General view of the mammalian retina

produce 'transient' responses, with just a few action potentials immediately after a change in illumination. They are called α cells. On the contrary, β cells give sustained responses to light.

Several retina models appear in the literature following these lines [3]. The studied configuration in this paper appears in Fig. 2 and it was partly reported by us [4]. Just two photoreceptors have been taken. This configuration is similar the one proposed by Dowling [3] to summarise the activity of the various retinal cells. As it can be seen, the receptor on the left is illuminated with a brief flash of light imposed on a dim background that illuminates both receptors, R1 and R2. A large response is observed in the stimulated receptor whereas the adjacent receptor that is not illuminated (right receptor) shows only a small response that probably reflects mainly the electrical coupling between the photoreceptor cells. Bipolar and horizontal cells are both activated by the receptors. The scheme of Fig. 2 shows that bipolar cell B1 is polarised strongly in a graded and sustained fashion by direct contacts with receptor R1. Moreover, this bipolar cell potential is antagonised by horizontal - bipolar cell B2 interaction. Bipolar cell B2 responds to indirect (surround) illuminations by depolarising. As it can be seen, the switch from hyperpolarizing to depolarising potentials along the surround illumination pathway occurs at the horizontal - bipolar junction.

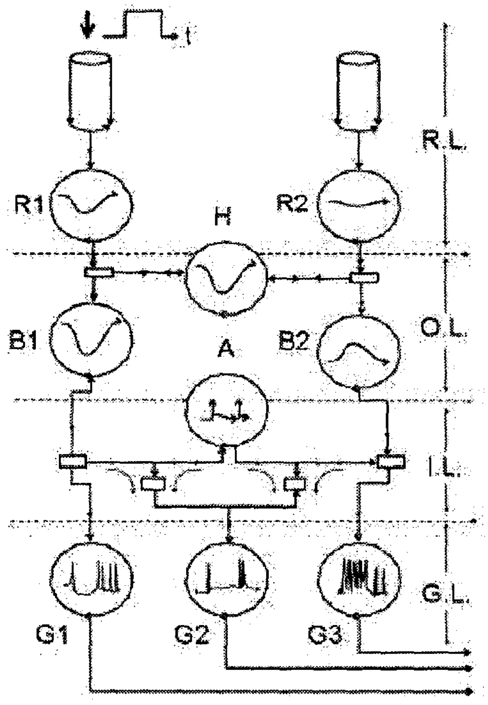

Figure 2.- Basic configuration employed as primary structure of the mammalian retina.

Amacrine cell, A, responds to light mainly with transient depolarizing potentials at the onset and cessation of spot illumination. The responses of the two basic types of ganglion cells found in the vertebrate retinas appear to be closely related to the responses of the input neurones to the ganglion cells. The G1 ganglion cell has a receptive field organisation very similar to that of bipolar cells. Central illumination hyperpolarises both the bipolar and ganglion cells, B1 and G1, in a sustained fashion, and surround illumination depolarises the bipolar B2 and ganglion G2 cells in a sustained fashion. This type of ganglion cells appears to receive most of its synaptic input directly from the bipolar cell terminals through excitatory synapses. The ganglion cells illustrated in Fig. 2 are off-centre cells but there are some other types present in the vertebrate retinas. Ganglion cell G2 responds transiently to retinal illumination, much as the transient amacrine cells do. This type of response is the one adopted in our model.

Although this model is a very simple one, it is very useful to implement most of the functions performed at the mammalian retina. More complicated models can be obtained directly from this one.

III. STRUCTURE OF THE FUNDAMENTAL BUILDING BLOCK

As it has been pointed out before, a simple cell has been the basis for the architecture of the proposed system. This cell has been employed by us as the main block for some structures in optical computing [5]-[7]. Its characteristics have been presented in several places and they may be synthesised as follows. The basic structure is shown in Fig. 3. It is composed by two non-linear elements: an on-off device and a SEED-like device. Their characteristics are shown at the inset of Fig. 3. It has two signals input, I_1 and I_2 as well as and two control signals, h and g. The output is a set of fourteen pairs of signals, boolean functions of the inputs. When some feedback is added, for instance connecting a part of the output from O_1 as control signal to

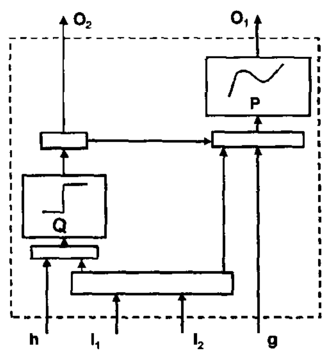

Fig. 3.- Basic structure of the elemental block for the retina and visual cortex architectures.

the P device, as well as a multilevel periodic input, some non-linear behaviour is obtained. Under certain conditions and with a certain type of feedback it is possible to obtain even a chaotic signal. Moreover, with no input, a periodic situation appears being the period a function of the feedback delay time. A detail of each one of the blocks in Fig. 3 appears in Fig. 4.

IV. MODEL SIMULATION

To develop a first study of the model feasibility, a computer simulation has been adopted. A general diagram is shown in Fig. 4. MATLAB tools have been employed.

There are two data signals to be applied to photoreceptors: a constant background signal and a pulses train. The second one represents short light flashes whereas the former one corresponds to the ambient light.

A gain constant in each channel, before the input of each cell, is added. Although it is not necessary in our present study, it has been added in order to maintain the possibility of incorporating a weight to the signals. This fact should be considered when higher level tasks would be added to the system.

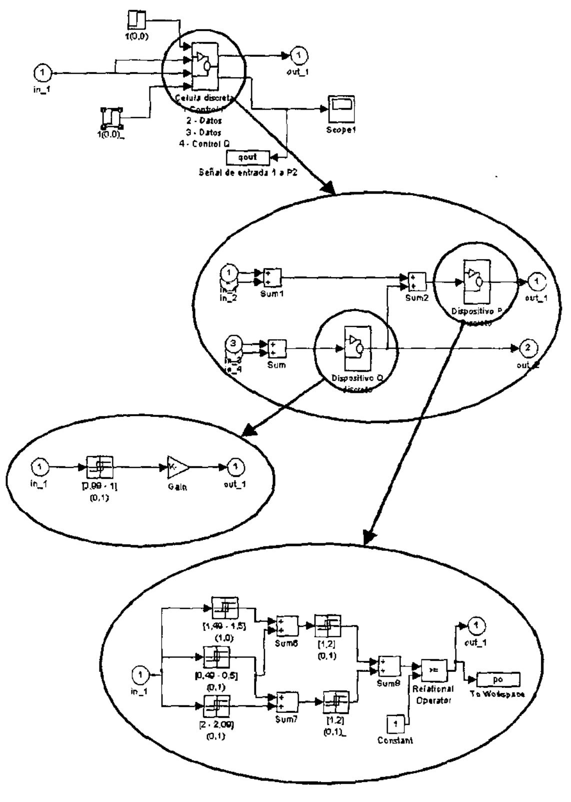

Fig. 4.- Details of the blocks in Fig. 3.

As it can be seen, the horizontal cell is fed by both receptors. The information is then transferred to the bipolar cells of each channel. Therefore, bipolar cells process the horizontal plus his corresponding receptor information. In the same way, the amacrine cell processes the signal obtained from the two bipolar cells. The result will be part of the input to the ganglion layer. The three different ganglion cells in this layer have responses depending on their inputs.

V. OBTAINED RESULTS

The results obtained for the above indicated configuration correspond to the ganglion cell behavior of the Dowling model. They are shown in Fig. 6. Amacrine cell must give a different output signal than the ones appearing at receptor, horizontal and bipolar cells. Its resting state is, in our case, a logic "1" and switches to a logic "0" at the beginning and at the end of light pulses. This switch is in the form of a brief impulse. After this peak, it returns to the resting state. Hence, its behavior is in the form of action potentials with a burst of just one pulse.

An important point to be said here is that, with this arrangement, the amacrine is in charge of detecting the illumination time on receptors. This aspect is not considered in the literature. The more important function customarily assigned to amacrine cells corresponds to spatial aspects of visual signals. We believe that this proposed temporal aspect needs to be considered in future works.

The composite signals from bipolar and amacrine

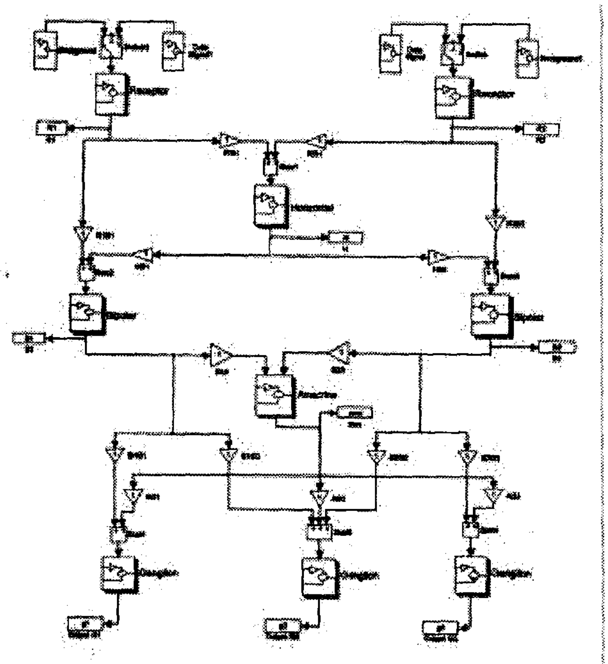

Fig. 5- Computer simulation of the retina model.

cells arrive to the ganglion cells from where the final signal is obtained. There are several possible responses from the ganglion cells. Three of them are in Fig. 2. The first one is a train of light pulses, its length being the same as that of the input flash. A periodic sequence of short pulses is always present in the third one. When there is light at the input, the pulses disappear. Finally, the second one shows a continuous train of pulses. It disappears just at the beginning and at the end of the initial flash.

The above indicated behavior corresponds to hyperpolarizing bipolar cells and off-center ganglion cells (G1 and G3) that respond to direct central illumination (left side in Fig. 2) by hyperpolarizing and to indirect (surround) illumination (right side) by depolarizing. The switch from hyperpolarizing to depolarizing potentials along the surround illumination pathway occurs at the horizontal-bipolar junction. The on-off ganglion cell (G2) receives strong inhibitory input from amacrine cells; these cells receive their excitatory input from both amacrine and bipolar cells.

This structure has the characteristic of being non-symmetric. This means that the behavior of the total retina layer is not the same if the light is coming from the right path than from the left path. Fig. 6 shows the responses when light impinges just into the left receptor. The three ganglion cells offer three different outputs.

V. CONCLUSIONS

A model of the mammalian retina has been reported in this paper. It was based on the employ of an optically programmable logic cell as basic unit for the five different types of retinal neurons, namely photoreceptor, horizontal, bipolar, amacrine and ganglion cells. Every one of them has been modeled with the same elemental unit. Just some minor changes in the internal or external connections have allowed simulating different behaviors.

The main fact of the reported model is its simple structure being able to give almost any possible output signal from ganglion cells.

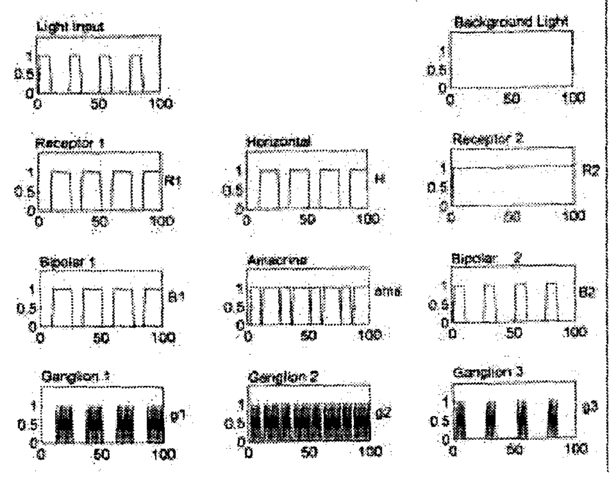

Fig. 6- Obtained responses from model in Fig. 5.

Although the presented model is composed by just two receptors, one horizontal, two bipolars, one amacrine and three ganglion cells, it could be extended to larger configurations. The main advantage of this structure is the possibility to build almost any retinal architecture with the use of a single basic structure as well as the possibility to obtain different ganglion outputs from a very simple structure. A further remark needs to be pointed out. According to the reported model, amacrine cells are in charge of detecting the illumination time on receptors. This fact has not been taken into account in any previous emulation and deserves a further study.

ACKNOWLEDGMENT

This work was partly supported by CICYT, grant TIC99-1131 and CAM "Comunidad Autónoma de Madrid", grant 07T/0037/2000.

REFERENCES

[1] *Neuro-vision Systems. Principles and Applications.* Madam M. Gupta and George K. Knopf, Eds. New York: IEEE Press. 1993.

[2] G.M. Shepherd, *Neurobiology*, New York: Oxford University Press. 1994.

[3] J. E. Dowling, *The Retina: An Approachable Part of the Brain.* Cambridge, MA: The Belknap Press of Harvard University Press, 1987.

[4] J.A. Martín-Pereda, A. González-Marcos and C. Sánchez-Guillén, "A model of the Mammalian Retina and the Visual Cortex. Disorders of vision". In *Proc. IEEE Conference on Engineering in Medicine and Biology.* Technical Digest CD-ROM 138-140. Amsterdam, 1996.

[5] A. González-Marcos and J.A. Martín-Pereda, "Digital chaotic output from an optically processing element", *Optical Engineering,* vol. 35, pp. 525-535, 1996.

[6] A. González-Marcos and J.A. Martín-Pereda, "Analysis of irregular behaviour on an optical computing logic cell". *Optics & Laser Technology*, vol. 32, pp. 457 – 466, 2000.

[7] A. González-Marcos and J.A. Martín-Pereda, "Method to analyze the influence of hysteresis in optical arithmetic units". *Optical Engineering*, vol. 40, pp. 2371-2385, 2001.